NASA/TM—2004-212972

Friction and Wear Characteristics of Cu-4Al Foil Bearing Coating at 25 and 650 °C

Malcolm K. Stanford and Christopher DellaCorte
Glenn Research Center, Cleveland, Ohio

March 2004

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Acknowledgments

The authors are grateful for the technical assistance provided by J.A. Buehler, D.J. Dixon, B.J. Edmonds, J.M. Lucero, V. Lukaszewicz, M.S. McQuater, J.H. Petersen, V.J. Sciortino, and L.D. Ward.

This report contains preliminary findings, subject to revision as analysis proceeds.

This work was sponsored by the Low Emissions Alternative Power Project of the Vehicle Systems Program at the NASA Glenn Research Center.

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Malcolm K. Stanford and Christopher DellaCorte
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio

Summary

The friction and wear performance of a Cu-4Al top foil coating has been investigated in Generation I foil air bearings. The copper alloy was applied by a novel deposition technique (*ion diffusion*) and the journal was coated with PS304, a plasma spray deposited high temperature composite solid lubricant coating. The ion diffusion coating process deposits a desirable smooth layer compared to other methods like cathodic arc deposition. The tribological performance of bearings with and without Cu-4Al foil coatings were evaluated through start-stop tests on an air bearing test rig at 25 and 650 °C. The results indicate that the Cu-4Al assists during the initial break-in period, gives more stable friction performance with respect to temperature, and appears to prevent top foil wear at high temperature. The measured load capacity coefficient was 0.5, which was comparable to earlier testing of more advanced design Generation III bearings coated with standard cathodic arc deposited Cu-4Al. However, further studies are needed to determine if deeper penetration of the copper alloy into the foil would help make the transition in friction behavior from contact with the Cu-4Al coated foil to contact with the base foil material more gradual. Also, future work is recommended to assess the performance of ion diffusion coatings with different Cu-based alloy compositions and to investigate the effect the coating has on the elastic modulus of the foil material.

Introduction

Foil air bearings (refs. 1 and 2) have been successfully implemented in advanced turbomachinery applications including turbochargers and generators with current activities directed toward aeropropulsion engines (refs. 3 to 5). A foil air bearing, illustrated schematically in figure 1, is a self-acting hydrodynamic bearing that uses ambient air as a lubricant during normal, high speed operation. During start-up and shut-down, when an air film is not present, sliding contact occurs between the shaft and the thin sheet metal top foil. To prevent excessive torque (friction) and wear of the sliding surfaces, solid lubricants are required (ref. 3). A NASA-developed composite solid lubricant coating, PS304 (ref. 6), applied to the journal by plasma spray deposition has been shown to be effective after an initial break-in period.

Previous studies have shown that the application of coatings to the top foil (fig. 1) further improves bearing performance by eliminating or minimizing the need for a break-in period (refs. 7 to 9). The foil coating facilitates the necessary development of a solid lubricant transfer layer during the initial period of operation and helps prevent galling type wear, which occurs when asperities on initially rough bearing surfaces are plastically deformed and welded to the opposing surface (refs. 10 and 11). In particular, a cathodic arc deposited (ref. 10) copper alloy (Cu-4Al) performed exceptionally well as a foil coating (refs. 8 and 9). Unfortunately, the surface roughness of the as-deposited coating was very high, a common problem with this deposition technique (ref. 10), necessitating post-deposition polishing, which is very expensive and impractical for the given application. Other deposition techniques such as sputtering can yield smoother Cu-Al films but often have poor adhesion. The purpose of the present investigation was to evaluate the performance of Cu-4Al applied to the foil by ion diffusion, a novel deposition technique which produces a relatively smooth as-deposited surface (ref. 12).

Experimental Procedures

Cu-4Al coatings were applied to 38 mm diameter by 38 mm long Generation I foil air bearings with a proprietary process that infuses ions of the desired material into the substrate, somewhat similar to a diffusion coating (ref. 13). Generation I bearings are of simple design, consisting of a single bump foil layer and single top foil and are described more fully in reference 14. For this study, the target material was a Cu-4Al alloy, but multiple targets may be used to produce the coating alloy *in situ*. Inconel X-750 witness coupons (39×27×0.1 mm) were coated along with the bearings to allow detailed analysis of the coating, including metallography, composition analysis and surface roughness measurements. Metallography was performed by sectioning witness coupons perpendicular to the coated surface and preparing the cross section for microscopic examination in epoxy mounting media. Composition was analyzed by energy-dispersive x-ray spectrometry (EDS). Surface roughness was measured using a stylus-type profilometer. Scratch hardness testing, an indication of wear resistance and adhesion, was performed on the witness coupons with and without a Cu-4Al coating using an automatic scratch tester with a 228 μm diamond stylus applying a linearly increasing load from 10 to 80 N at a rate of 100 N/min over a distance of approximately 5 mm. The width of the scratch channel was measured at three points along the widest portion of the channel using commercially available software that interfaces with the scanning electron microscope (SEM).

Bearing friction and wear performance was evaluated with a foil air bearing test rig (ref. 8) at approximately 14,000 rpm using journals coated with PS304 operating against bearings with and without Cu-4Al foil coatings. The rig performed 30,000 start-stop cycles on each bearing at 25 and 650 °C with a 10.3 kPa contact stress. Bearing torque (tangential force) was measured throughout the test and the torque at the beginning and end of each cycle (start-stop torque) was recorded. A complete cycle typically lasts approximately 20 sec. For the first two thirds of the cycle, the spindle motor drive is activated and, within a few seconds, the journal accelerates to full rotational speed (14,000 rpm). Above approximately 4,000 rpm, a hydrodynamic air film is formed, which lubricates the journal and supports load (ref. 3). The hydrodynamic film formation is known as *lift-off* because the bearing shaft lifts away from the foil. Then, during the last third of the operating cycle, the spindle motor is deactivated and the journal coasts to a halt. The start-stop torque is considerably higher than the torque attained during normal operation (while an air film is present) because of sliding contact between the journal and the foil (refs. 1,2, and 8). The average of five typical stopping torque measurements was used for each data point graphed. After the start-stop cycle evaluation, the system friction performance was characterized by increasing the normal load in 2.45 N increments up to approximately 45 N, as outlined by DellaCorte et al. (ref. 3). *Load capacity,* which is the maximum load the bearing can support at steady state, was determined for coated and uncoated foil bearings by calculating the load capacity coefficient D (refs. 8 and 9). The average of three stopping torque measurements was reported for each load, from which the average friction force due to the bearing was determined. The coefficient of friction was then calculated as the slope of the least-squares fit of friction force as a function of static load, as shown schematically in figure 2 (ref. 4). The intercept of this line is the bearing preload, or the spring force within the system due to the designed interference fit between the bearing inner diameter and the shaft outer diameter.

Journal wear was measured with a micrometer at the center and two outer edges of the contact area. Foil wear was measured at the top dead center location of the top foil, which is the location of highest wear during start-up and shut-down. These testing procedures are described in more detail elsewhere (refs. 4 and 5).

Results and Discussion

An optical photomicrograph of an ion diffused Cu-4Al coated foil cross section is shown in figure 3(a). In the photomicrograph, it can be seen that the copper alloy has been infused into the top and bottom edges of the foil substrate, giving it a bronze appearance compared to the grey color of the nickel-based alloy substrate. This result differs from conventional coating techniques, such as the cathodic arc deposited Cu-Al shown in figure 3(b), by which the coating material is deposited on the surface of the substrate.

The average depth of Cu-4Al penetration from the ion diffusion technique was 13 ± 2.1 μm, based on image analysis measurements. The measurements were performed by recording the distance perpendicular to the edge of the foil to the end of the bronze-colored region in 30 locations on the image. EDS analysis confirmed the presence of the copper alloy along a cross section of a coated witness coupon. Figure 4 is an SEM photomicrograph showing a cross section of coated top foil material (Inconel X-750), with an infusion of Cu-4Al visible along the top edge of the coupon. The numbered locations in figure 4 correspond to the EDS spectra with the corresponding letter in figure 5. The nominal composition of Inconel X-750 is listed in table 1 for comparison. As seen in the spectra, the presence of copper decreased sharply as the measurement location moves away from the top (outer) edge of the foil (the aluminum peak at approximately 1.5 keV is not labeled). Specifically, copper comprised 17, 4, 2, 1 and 1wt% of the sample, sequentially from locations 1 through 5. This suggests a graded Cu-4Al concentration with the highest amount at or near the edge of the foil. The photomicrograph (fig. 3) showing what appears to be a well-defined Cu-4Al border may be deceiving, however, because though the edge of the diffusion depth appears to be distinct in the two-dimensional image, the penetration of Cu-4Al very likely varies throughout the volume of the substrate (perpendicular to the plane of the image). The EDS probe will also collect chemical composition from a volume of approximately 1 μm^3 (below the plane of the image), which may include copper-free substrate and produce lower Cu concentrations.

Surface roughness and scratch test measurements for coated and uncoated top foils are listed in table 2. The average roughness value (R_a) for the uncoated foils was 0.1 μm and is the same as previously reported (ref. 8). The roughness of the Cu-4Al coated foil was measured to be approximately five times greater than the uncoated value. For comparison, the surface roughness of cathodic arc deposited coatings mentioned previously was R_a = 3.6 μm, which is seven times greater than the as-deposited surface roughness obtained from the current process, which required subsequent finish grinding to achieve a desired 0.4 μm finish. Since the ion diffusion coating technique is not a line-of-sight process, the entire bearing had a bronze or copper-colored appearance and had a gritty texture as if covered with a light dusting of fine sand. However, the foils became smoother after sliding contact with the journal during testing with areas of light green (copper oxide).

Figure 6 is a set of scanning electron photomicrographs showing portions of scratch channels on an uncoated and Cu-4Al coated Inconel X-750 foil specimen. The area surrounding the scratch channel on the coated specimen is covered with globules of material that may account for the gritty texture mentioned previously. There is also flakey wear debris on the perimeter of and within the scratch channel. Based on post-test optical microscope and EDS observations, the stylus wore through the Cu-4Al coating approximately one third of the distance along the length of the scratch channel due to increased stylus penetration at a load of approximately 33 N. The increase in the scratch channel width from coated (219 ± 8 μm) to uncoated (222 ± 6 μm) foil specimens was essentially negligible indicating no change in hardness.

Figure 7 shows portions of scratch channels in cathodic arc deposited Cu-4Al. Figures 7(a) and 7(b) show the beginning and end of a scratch channel in the as-deposited coating, while figures 7(c) and 7(d) show the same features in the ground coating. The change in scratch channel width from the ion diffusion coating to the ground and as-deposited cathodic arc coating were approximately 7 and 37 percent, respectively. The difference in scratch channel width between the ground cathodic arc coating

(235 ± 9 μm) and the ion diffusion coating (219 ± 8 μm) was within the range of statistical variation again indicating no change in hardness. The significantly wider scratch channel in the as-deposited cathodic arc coating is probably due to the greater thickness of the coating and the relatively low hardness of the coating material.

Wear results are listed in table 3. Compared to uncoated Inconel X-750 foil surfaces, the Cu-Al coated foils wore more during initial room temperature tests. The foil wear for coated and uncoated foils was equivalent after 20,000 and 30,000 cycles. The cumulative foil wear was generally higher for these room temperature tests than in previous studies where it was only 10 μm after 30,000 cycles (ref. 3). This difference was attributed to bearing design since the Generation I bearings tested here experience a higher lift-off speed and hence more sliding than the Generation III bearings tested previously (ref. 3). At high temperature, the uncoated foil wear was comparable to previous testing. However, the Cu-4Al coated foil had no wear throughout the test. Journal wear for the room temperature tests was roughly the same for either coated or uncoated top foils, but both were approximately double that of the previous investigation. The journal wear at 650 °C was generally higher with the Cu-4Al coated bearing than with the uncoated bearing, but both journals wore at a much greater rate than previously measured in similar tests, again, most likely due to differences in bearing design.

Table 4 lists the coefficient of friction and spring preload data for the studied foil bearing systems. Figure 8 is an example plot used to calculate these data for an uncoated bearing run at room temperature. The coefficient of friction for the Cu-4Al coated bearing was 16 percent lower than for the control case (uncoated foil) at room temperature. However, the coated bearing had a 19 percent higher coefficient of friction than the uncoated bearing at high temperature. The coefficient of friction was lower at 650 °C than at room temperature for the control case, confirming earlier results. However, with Cu-4Al foil coating, the friction coefficient was essentially the same regardless of temperature. The reason for this behavior is not yet clear, but the issue is under continued study. Additionally, other copper alloys should be explored for this application. For example, increasing the concentration of aluminum in a Cu-Al solid solution tends to increase the strength (thus, elastic modulus) of the material (refs. 15 and 16). Furthermore, Cu-4Fe-11Al is typically used in bearings, bushings and other types of mechanical systems requiring friction and wear reduction (ref. 17). Since ion diffusion allows coating deposition at various concentrations and from multiple source targets, investigation of the performance of additional copper alloy top foil coatings would be valuable to the tribology community.

Bearing stopping torque at several intervals of each test is plotted in figure 9. For both coated and uncoated foils, the stopping torque was generally lower at 650 °C than at room temperature. For the room temperature tests, the bearing with the Cu-4Al foil coating had slightly lower stopping torque at the start of the test. Thereafter, the two bearings performed equivalently. For coated bearings the rise in stopping torque at 5,000 cycles nominally coincides with the removal of the approximately 13 μm thick foil coating. These data compare favorably to previous bearing results where the torque was 238 N·mm after 30,000 cycles (ref. 3). It is possible that the foil coating provided solid lubrication during the initial portion of the test, aiding transfer layer formation and allowing the bearing to break in. However, after the copper alloy was worn away, this benefit was lost. Deeper Cu-4Al penetration may allow the top foil coating to remain until the journal forms the desirable transfer layer.

During high temperature tests, referring again to figure 9, the system with the Cu-4Al coated foil again had slightly lower torque at the beginning of the test. However, this bearing had higher torque from this point forward.

The maximum loads supported by the uncoated and Cu-4Al coated bearings at room temperature were 8 and 10 kg, respectively, with load coefficients of 0.4 and 0.5, correspondingly, indicating that the Cu-4Al coating can improve performance.

Concluding Remarks

The purpose of this investigation was to evaluate the performance of compliant surface air bearing with an ion diffusion deposited Cu-4Al top foil coating and compare the results to uncoated and cathodic arc coated bearings. The following remarks reflect the current interpretation of the results:

1. The employed process infuses the copper alloy into the foil substrate, which differs from conventional coating techniques, like cathodic arc deposition, which applies coating material to the substrate surface.
2. The surface roughness of the ion diffusion coated foil was approximately five times greater than that of the uncoated foil but seven times less than the coatings produced by cathodic arc deposition. During initial testing, the surface became smoother (*in situ* polishing).
3. Deeper penetration of the Cu-4Al coating material into the top foil substrate may enable a more gradual transition to bare foil sliding characteristics.
4. Further research is required to assess the effect different Cu-Al alloy compositions may have on friction, wear, and the modulus of the foil, especially at high temperatures.
5. It appears that the ion diffusion deposition is a viable method to apply tribological coatings (like Cu-Al) to foil bearing surfaces.

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Table 1. Nominal composition of Inconel X-750 bearing top foil material

Element	Weight percentage
Ni	73
Cr	15
Fe	7
Ti	2.5
Nb	0.9
Al	0.7
Cu	0.25
C	0.04

Table 2. Selected physical characteristics of coated and uncoated top foils

	Surface Roughness, µm		
Condition	Average roughness, R_a	Roughness depth, R_z	Maximum scratch channel width, µm
Uncoated Inconel X-750 foil	0.10 ± 0.01	0.91 ± 0.27	222 ± 6
Foil with ion diffusion coating	0.51 ± 0.15	6.12 ± 1.13	219 ± 8
Foil with as-deposited cathodic arc deposited coating	4.26 ± 1.09	2.84 ± 1.32	300 ± 0
Foil with ground cathodic arc deposited coating	0.46 ± 0.41	2.53 ± 1.04	235 ± 9

Table 3. Wear results

Number of cycles	Cumulative maximum diametral journal wear				Cumulative foil wear at TDC			
	Uncoated foil/ 25 °C	Cu-4Al coated foil/ 25 °C	Uncoated foil/ 650 °C	Cu-4Al coated foil/ 650 °C	Uncoated foil/ 25 °C	Cu-4Al coated foil/ 25 °C	Uncoated foil/ 650 °C	Cu-4Al coated foil/ 650 °C
5,000	18 µm	20 µm	8 µm	15 µm	0 µm	2 µm	6 µm	0 µm
10,000	30 µm	30 µm	8 µm	15 µm	5 µm	15 µm	6 µm	0 µm
20,000	38 µm	46 µm	15 µm	15 µm	20 µm	20 µm	6 µm	0 µm
30,000	43 µm	46 µm	25 µm	114 µm	36 µm	36 µm	11 µm	0 µm

Table 4. Bearing tribological properties

Test condition	Coefficient of friction[a]	Spring preload, g
Uncoated foil/25 °C	0.43	1076
Cu-4Al coated foil/25 °C	0.36	2047
Uncoated foil/650 °C	0.32	435
Cu-4Al coated foil/650 °C	0.37	13

[a]Measured at loads ranging from 10.3 to 30.6 kPa; the correlation coefficient (R^2) ranged from 0.94 to 0.99.

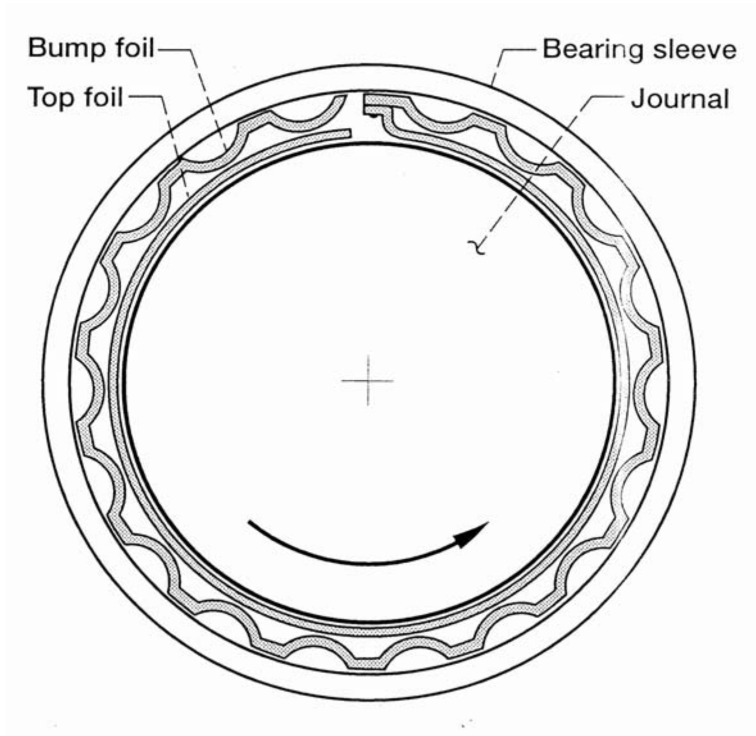


Figure 1. Schematic representation of foil air bearing cross section showing the compliant top foil.

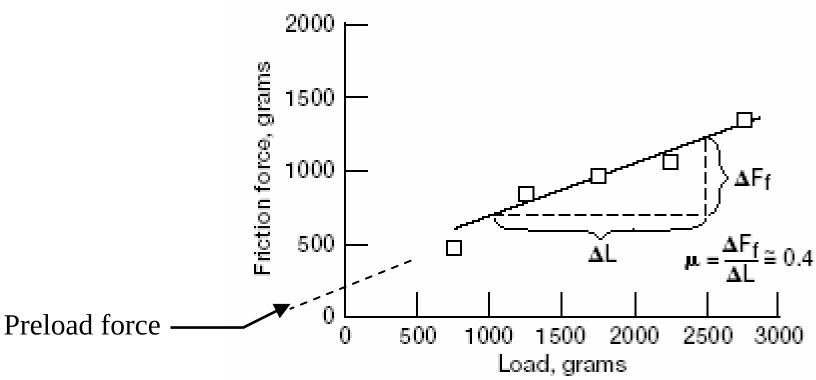


Figure 2. Graphical example of friction coefficient calculation (ref. 4).

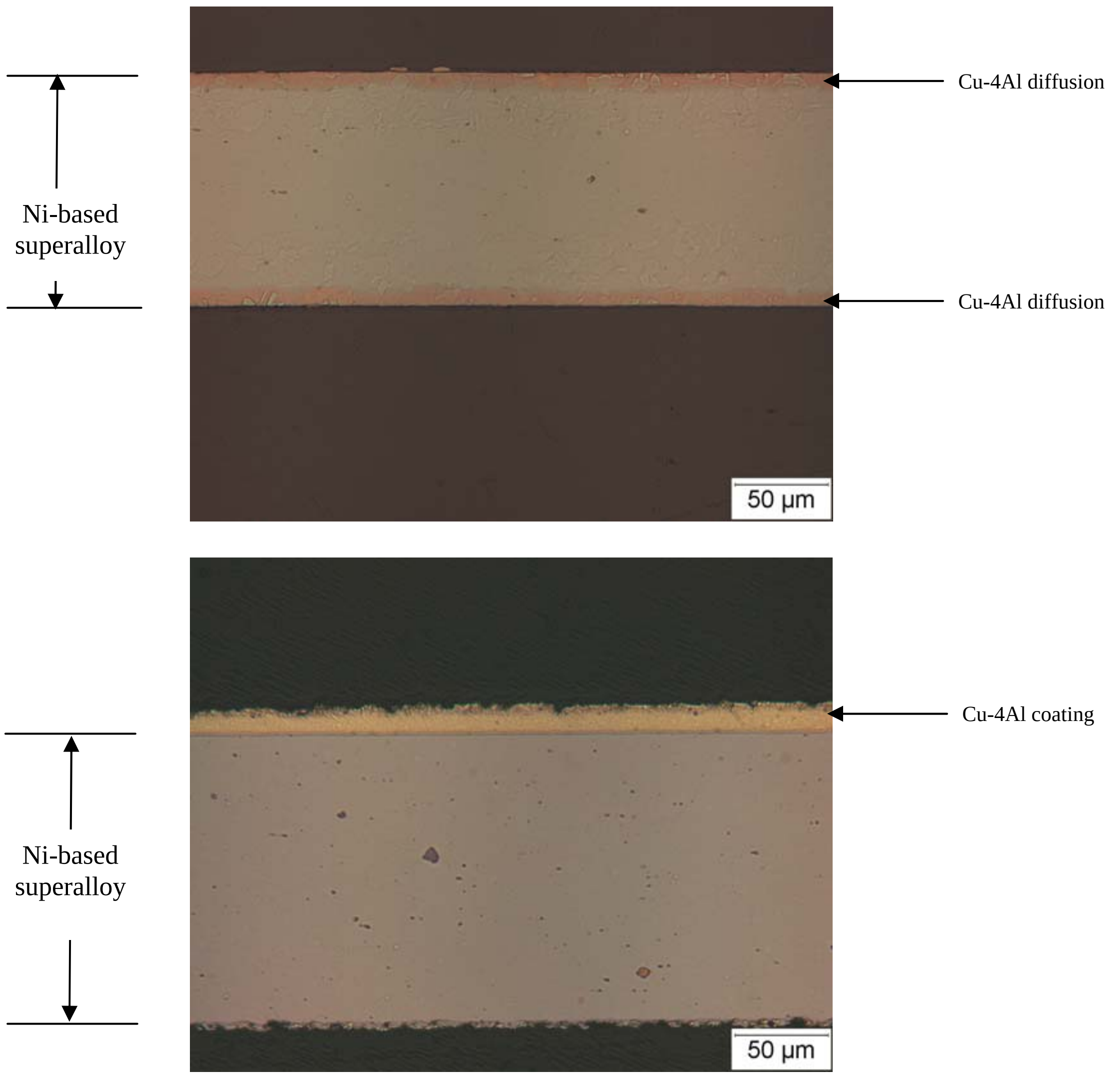


Figure 3. Optical photomicrograph of (a) ion diffusion and (b) cathodic arc Cu-4Al coated foil cross section (original magnification 200×).

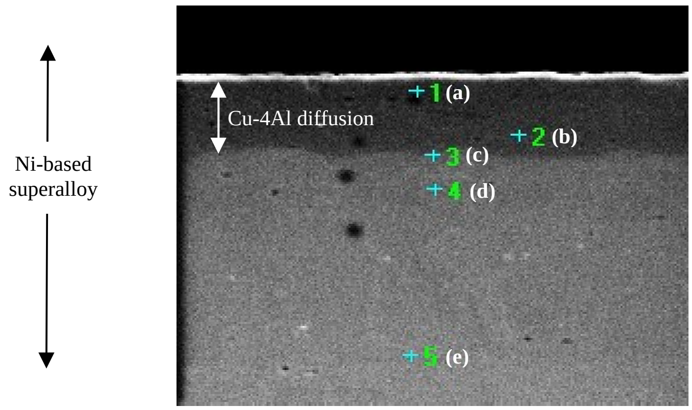
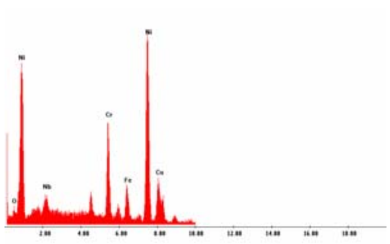
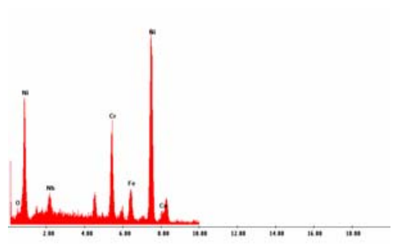


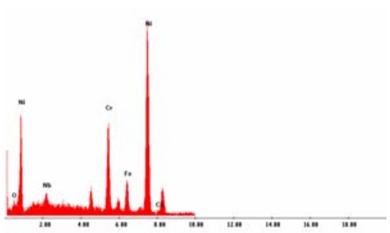
Figure 4. SEM photomicrograph (original magnification 500×)
of coated foil cross section showing five locations
((a) through (e)) of EDS analysis.



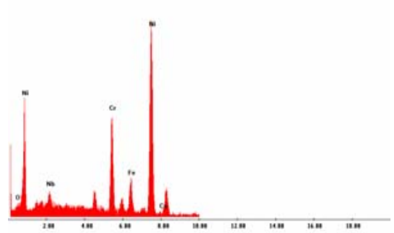
(a) 12wt% Cu



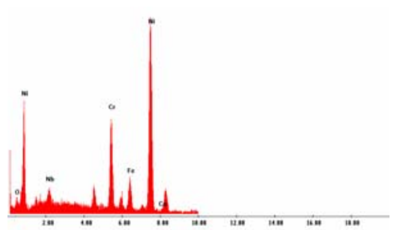
(b) 4wt% Cu



(c) 2wt% Cu



(d) 1wt% Cu



(e) 1wt% Cu

Figure 5. EDS spectra from locations (a) through (e) in figure 4.

(a) (b) (c) (d)

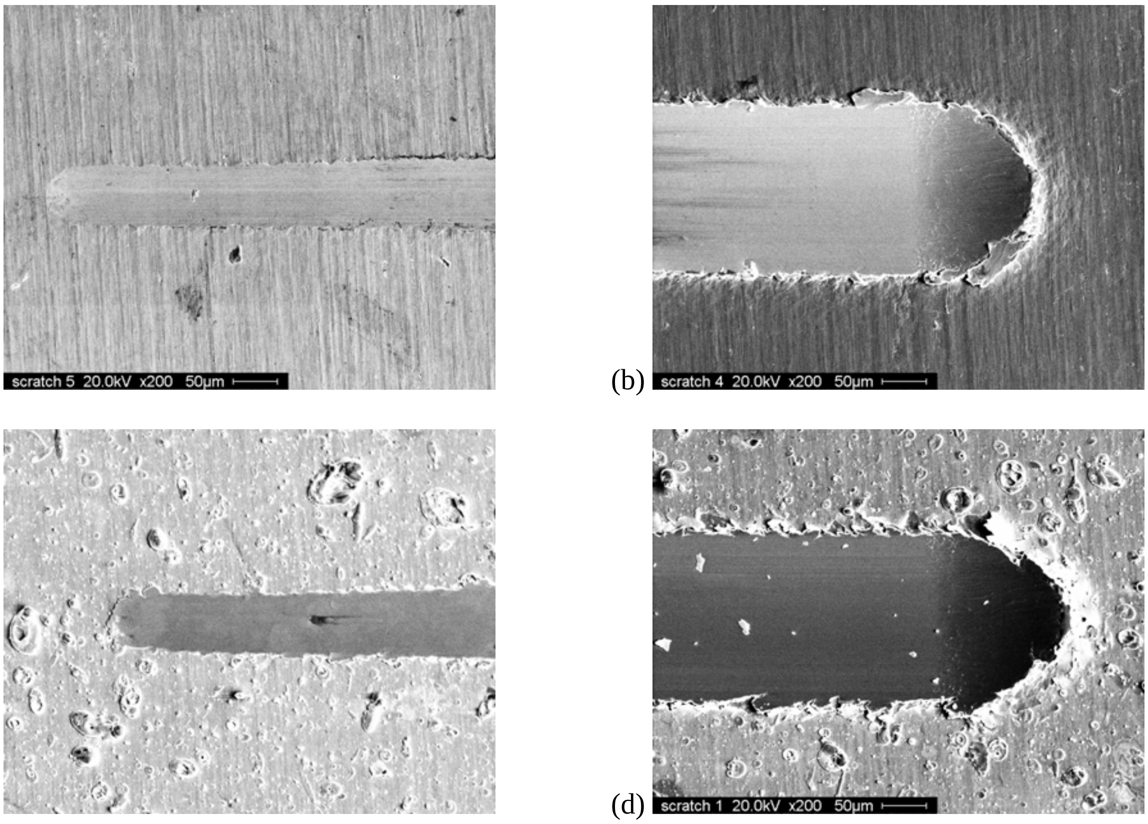


Figure 6. Scanning electron photomicrograph of scratch channels on (a) uncoated foil at start of channel, (b) uncoated foil at end of channel, (c) ion diffusion Cu-4Al coated foil at start of channel, and (d) ion diffusion Cu-4Al coated foil at end of channel.

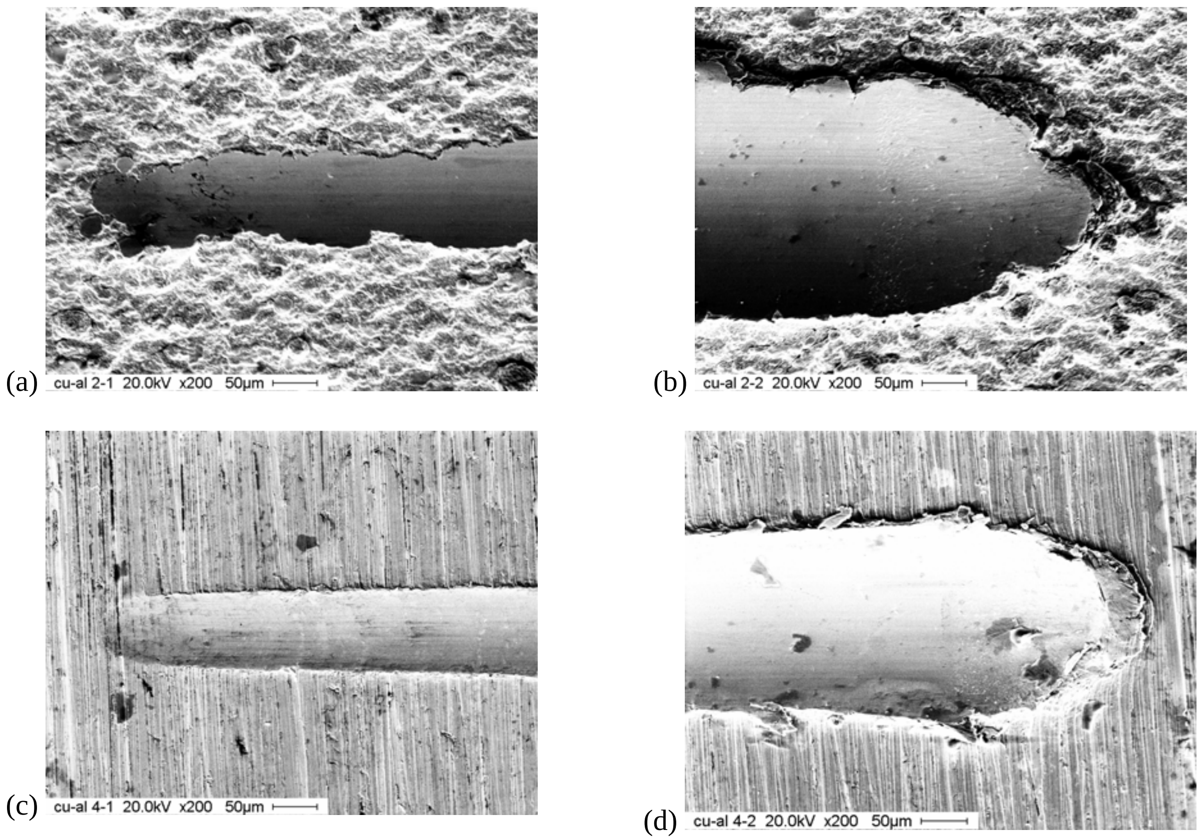


Figure 7. Scanning electron photomicrograph of scratch channels in cathodic arc deposited Cu-4Al (a) on as-deposited coating at start of channel, (b) as-deposited coating at end of channel, (c) ground coating at start of channel, and (d) ground coating at end of channel.

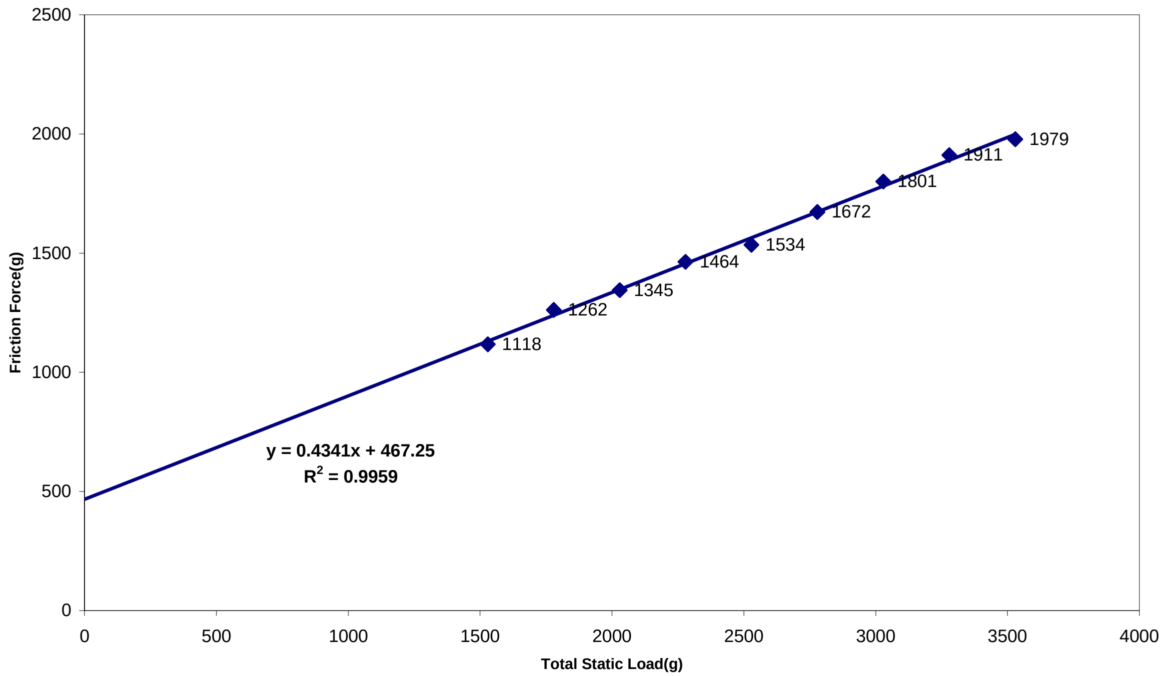


Figure 8. Plot of bearing friction force versus applied load for an uncoated top foil at 25 °C.

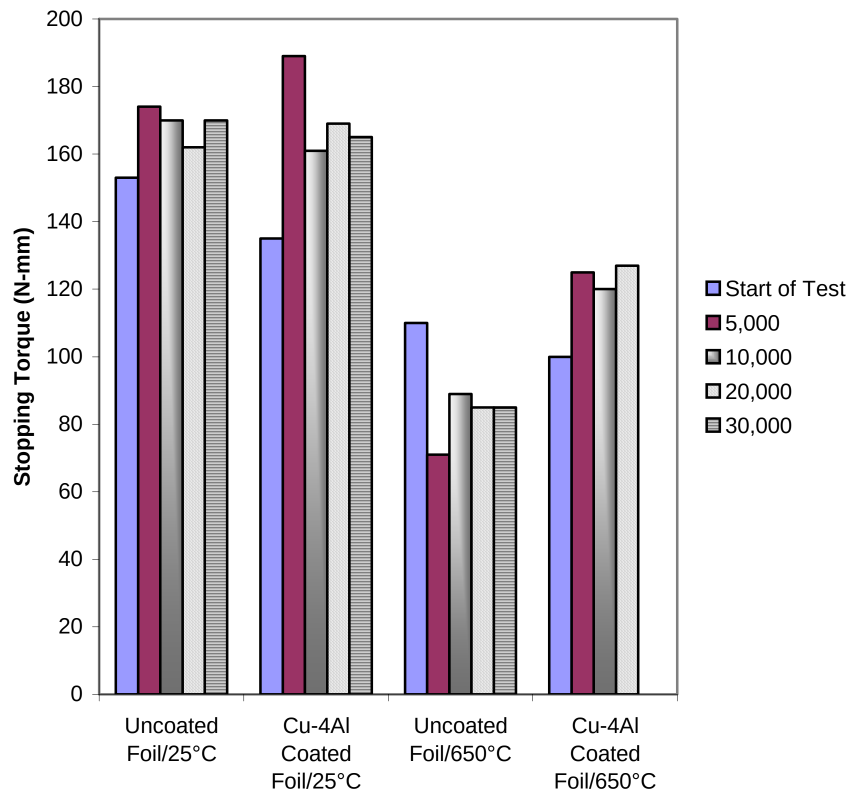


Figure 9. Bearing stopping torque (test was terminated early due to problem with test rig).

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. AGENCY USE ONLY (*Leave blank*)	**2. REPORT DATE**	**3. REPORT TYPE AND DATES COVERED**
	March 2004	Technical Memorandum

4. TITLE AND SUBTITLE

Friction and Wear Characteristics of Cu-4Al Foil Bearing Coating at 25 and 650 °C

5. FUNDING NUMBERS

WBS–22–708–18–04

6. AUTHOR(S)

Malcolm K. Stanford and Christopher DellaCorte

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
John H. Glenn Research Center at Lewis Field
Cleveland, Ohio 44135–3191

8. PERFORMING ORGANIZATION REPORT NUMBER

E–14445

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, DC 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

NASA TM–2004–212972

11. SUPPLEMENTARY NOTES

Responsible person, Malcolm K. Stanford, organization code 5960, 216–433–3387.

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Unclassified - Unlimited
Subject Category: 23 Distribution: Nonstandard

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12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 words)***

The friction and wear performance of a Cu-4Al top foil coating has been investigated in Generation I foil air bearings. The copper alloy was applied by a novel deposition technique (ion diffusion) and the journal was coated with PS304, a plasma spray deposited high temperature composite solid lubricant coating. The ion diffusion coating process deposits a desirable smooth layer compared to other methods like cathodic arc deposition. The tribological performance of bearings with and without Cu-4Al foil coatings were evaluated through start-stop tests on an air bearing test rig at 25 and 650 °C. The results indicate that the Cu-4Al assists during the initial break-in period, gives more stable friction performance with respect to temperature, and appears to prevent top foil wear at high temperature. The measured load capacity coefficient was 0.5, which was comparable to earlier testing of more advanced design Generation III bearings coated with standard cathodic arc deposited Cu-4Al. However, further studies are needed to determine if deeper penetration of the copper alloy into the foil would help make the transition in friction behavior from contact with the Cu-4Al coated foil to contact with the base foil material more gradual. Also, future work is recommended to assess the performance of ion diffusion coatings with different Cu-based alloy compositions and to investigate the effect the coating has on the elastic modulus of the foil material.

14. SUBJECT TERMS

Coatings; Lubrication; Solid lubricants; Bearings

15. NUMBER OF PAGES

18

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	**18. SECURITY CLASSIFICATION OF THIS PAGE**	**19. SECURITY CLASSIFICATION OF ABSTRACT**	**20. LIMITATION OF ABSTRACT**
Unclassified	Unclassified	Unclassified	